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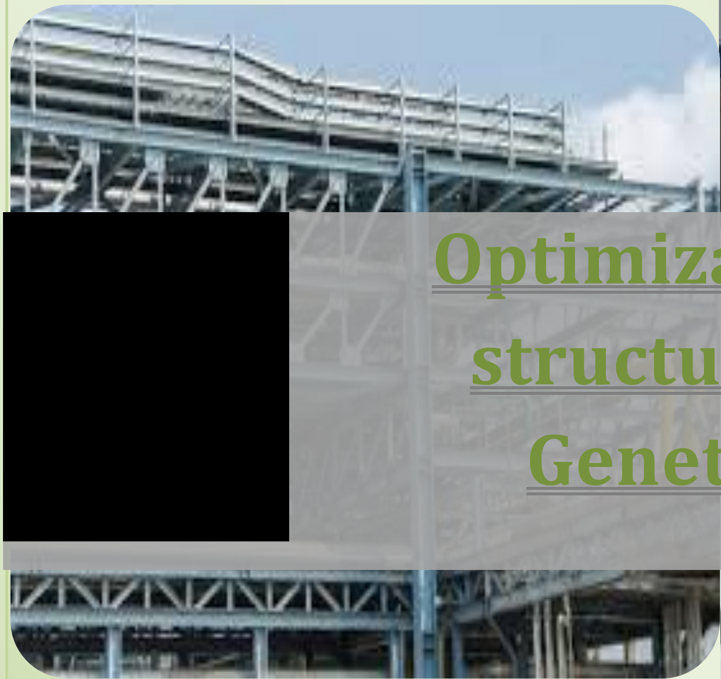

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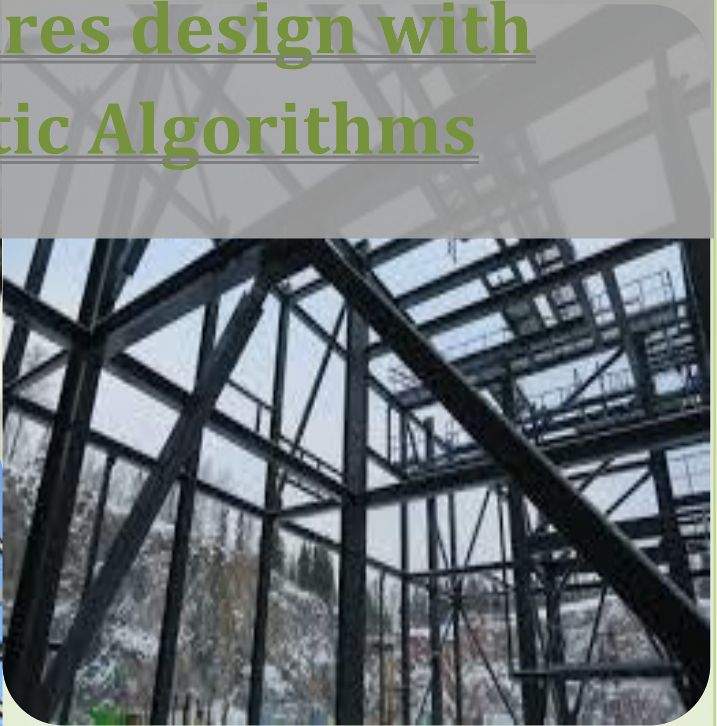
Optimization of the steel structures design with Genetic Algorithms



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Plan

- **Introduction**
- **Description**
- **Formulation of the global design problem**
- **Illustration**
- **Perspectives of enlargement of the field of study**
- **Application in Morocco**
- **Conclusion**

I. Introduction

Since always, designing a project consists of using generally a certain IT tool based on algorithms allowing the design of projects, which are in our case projects in the field of civil engineering.

However, the choice behind this study sums up in the fact that these algorithms are often used to design in depth stages of the project. On the other hand, for the pre-project stages, there are not many, only few of them are invented to help in this purpose.

Consequently, this dilemma leads to serious situations for a construction project's life in the long term. Indeed, as it is the case, a significant part of the total project cost is involved at the stage of the Steel Construction production process. It is therefore necessary to ensure that the decisions made during this phase are consistent. On the other hand, when the integration of technical constraints upstream is insufficient, it sometimes leads to inconsistencies and requires the reconsideration of solutions proposed upstream. This can be the source of additional costs and delays in the implementation.

Therefore, the need to work in this field becomes more required and researchers have become more interested in advancing optimization techniques for preventing uncontrolled cases especially that civil engineering is a dynamic field and we can assume that by finding optimal solutions to it, economy and other sectors will boost with no doubt.

Among the methodologies that have been developing, we find solving the problem of the global design of steel structures by using Genetic Algorithms.

These specific algorithms have lofty ambitions: They aim locally to help the engineers belonging to the design offices to **make relevant decisions from the stage of pre-project design**. However, globally its crucial purpose is to **reduce the cost of projects**.

Questions

How these algorithms are they used to reduce the cost of steel structures without causing damage to their components and a risk to the life of a construction project as well as not being a source of additional costs and delays in the implementation? How are they working? Are there any intentions to develop this technique? Is there any chance to implement them in Morocco if they are not nowadays?

II. Description

1. Situation

It is crystal-clear that design phase is the time when the design office's engineers could prevent the global optimization of production costs by using different technical tools to verify the feasibility of the structure, with regard to many things as structural constraints, implementation, etc.

However, for **steel structures**, these verifications take place once the designer has made the main choices: the shape of the structure, the layout of the different components, the load bearing and the foundation system…

These choices influence the feasibility of the project: technical and economic characteristics and by that the execution of the work. As a result, they give birth to additional costs.

Turning on to another angle which is the fact that reducing the weight of the structure in order to minimize projects' costs, is not at all a **profitable and cost-effective** act since the cost of a framework composes mainly of the cost of labor depending on the degree of complexity of the assemblies.

As a solution to this dilemma, many design offices' engineers adopt the next solution that researchers developed.

2. Solution

The optimization technique known as Genetic algorithms alias **GA** takes into consideration Almost every details as the material costs, manufacturing and assembly of the metallic superstructure and the costs of foundation systems' realization as well as the dimensional characteristics of the elements, the nature of the supports and the design of the assemblies.

- As a result, **these algorithms could minimize the cost of steel structures, seen from many angles, as much as possible without causing any damage or additional costs**.

We will start with formulating the problem generally and after that implement it on genetic algorithms.

III. Formulation of the global design problem

i. Euro code 3’ dimensioning constraints:

With the noble aim of minimizing the global cost of the steel structures, the global design must take respect the dimensioning constraints defined by the **Euro code 3** regulations.

Fortunately, we could integrate these regulations that focus on the modeling of assemblies in an easy way in all the algorithms and we could formulated them as below:

1. Cross-sections Resistance:

$$\frac{N_{SD,i}}{N_{R,i}} + \frac{M_{SD,i}}{M_{R,i}} < \gamma_M$$

For i in range (1, n), n: Number of elements.

Nsd and Msd: **Design** **normal** force and **bending** moment.

Nr and Mr: **Resistant** **normal** force and **bending** moment.

γ_M **:** Partial **safety** factor;

2. Buckling stability of the elements:

$$\frac{N_{SD,i}}{x_i N_{R,i}} + \frac{k_i M_{SD,i}}{M_{R,i}} < \gamma_M$$

For i in range (1, np), np: Number of columns.

x : **Buckling coefficient**; k: **moment coefficient**;

3. The limitation of the deformations of the bent elements:

$$v_i \le v_{lim,i}$$

For i in range (1, nb), nb: number of beams.

vi: **Deformation** of an element with respect to the line of its supports;

4. The limitation of the horizontal deformations of frames:

$$u_i \le u_{lim,i}$$

For i in range (1, nn), nn: number of nodes;

ui: **Horizontal** displacement at the head of a column.

After considering these dimensioning constraints, let us turn on to the evaluation of costs.

ii. Evaluation of the production cost of a steel structure

The global cost of the structure includes:

The cost of the steel superstructure: It includes these costs: The cost of the **profiles**, the **beam-post assembly** elements, the **attachments** at the foot of the posts, the cost of **manufacturing** the various components in the workshop as well as the cost of assembly on site.

The cost of the foundations: It includes theses costs: The cost of **earthworks**, materials and **foundations**.

iii. Optimization variables

The design variables are of three types:

1. Dimensional characteristics of the elements:

The choice of elements of the structure will be from a list of standard profiles.

The choice of the beams will be from a list of **18** elements of **IPE** beams with a height varying from **80 to 600 mm**. For the columns, we will consider the **HEB** type with a height varying from **100 to 600 mm**.

2. Type of supports

There are two configurations: An **articulated column foot** (column fixed by an end plate only) and an **embedded column foot** (column fixed by a stiffened end plate).

3. Type of connections

For **beam** and **column** connections, five connection types that we will consider: Overhanging end plate- overhanging end plate assembly with stiffeners- end plate without protrusion- core angles- core and sole angles

iv. Global optimization of steel structures

The objective function is the minimization of the global cost of the structure construction **Cg** with respect of the conditions or constraints.

The global cost **Cg** is a function of the variables: dim, Na and Nn. The formulation of the optimization problem takes the expression: **Min Cg (dim, Na, Nn)**

dim: Vector of the dimensional characteristics of the bars (sections, lengths of the bars...),

Na: Vector of the nature of the supports, i.e. the connections of the structure with the external environment,

Nn: Vector of nodes' nature.

The global cost **Cg** is composed of the cost of the **steel superstructure**: **Cs** and the cost of the **reinforced concrete foundation mass**: **Cf**

Consequently, **Cg= Cs+ Cf**

These two costs are themselves composed of other costs. The cost **Cs** is composed of cost of the **materials of the profiles and assemblies**: **Cma**, the cost of **manufacturing** in workshop: **Cfa** and the cost of **assembly of the various elements** on site: **Cmo**

Consequently, **Cs= Cma+ Cfa+ Cf**

The cost **Cf** is composed of the cost of **earthworks**: **Ct** and production cost of the **foundations**: **Cp.**

Consequently, **Cf= Ct+ Cp**

A common solution is to incorporate into the evaluation function penalties for individuals who violate the constraints. These penalties usually depend on the number and/or the "importance" of the violated constraints.

Among the different forms of penalties, there is a simplified form, which consists in using a normalization of the constraints in order to give them the same weight in the objective function.

We could write a constraint in the form: $f_i(dim, Na, Nn) \leq b_i$ and transformed into the following normalized form: $g_i(dim, Na, Nn) = \frac{f_i}{b_i} - 1 \leq 0$

This penalization method allows minimizing the following function F without constraints:

$F = C_g(1 + K \sum_1^m P_i)$ K is a constant to be chosen according to the problem and Pi is the value of the penalty evaluated as follows: $P_i = \begin{cases} g_i \; for \; gi \geq 0 \\ 0 \;\; for \; gi \leq 0 \end{cases}$ i=1…m: Total number of constraints.

The fact that the simultaneous consideration of three types of optimization variables considerably increases the size of the search space, the non-linearity of the objective function and constraints as well as the discrete nature of the design variables require using meta heuristic (GA) since they are able to solve easily such types of problems.

For that reason before implementing GA to steel structures, what are they?

1. Genetic algorithms

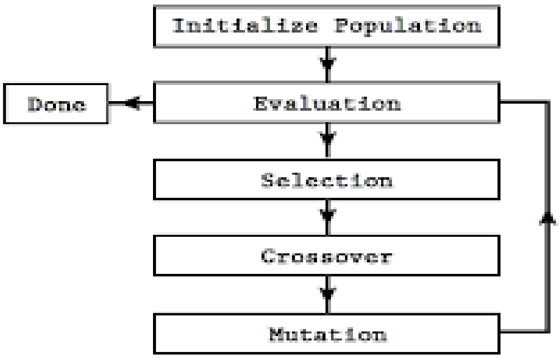
A **Genetic Algorithm** (**GA**) is a search heuristic inspired by the process of natural selection that belongs to the larger class of **Evolutionary Algorithms** (EA) (**Charles**

Darwin’s theory of natural evolution). It reflects the process of **natural selection** where the fittest individuals are selected for reproduction in order to produce offspring of the next generation. **So, how this natural selection works?**

- Select the fittest individuals from a population.
- They produce offspring inheriting the characteristics of the parents.
- If parents have better fitness, their offspring will have a better chance at surviving. This process keeps on iterating.
- At the end, we will find a generation with the fittest individuals.

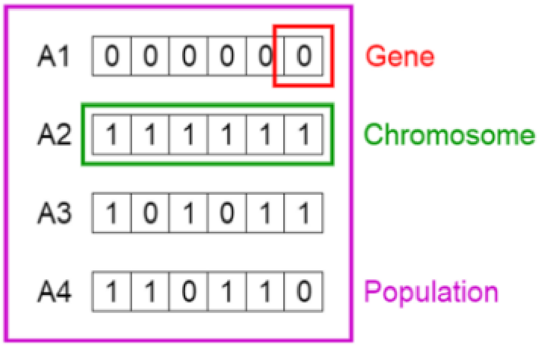
In this algorithm, there are 5 phases: **Initial population**, **fitness function**, **selection**, **crossover and mutation.**

```
START
Generate the initial population
Compute fitness
REPEAT
    Selection
    Crossover
    Mutation
    Compute fitness
UNTIL population has converged
STOP
```



1. Initial population

- It begins with a **Population (**a set of individuals). Each individual is a solution to the problem desired to solve.
- **Genes** (variables) joined to form a **Chromosome** (solution) characterize it. We use strings (binary values of 0 and 1) to represent genes.



A1	0	0	0	0	0	0
A2	1	1	1	1	1	1
A3	1	0	1	0	1	1
A4	1	1	0	1	1	0

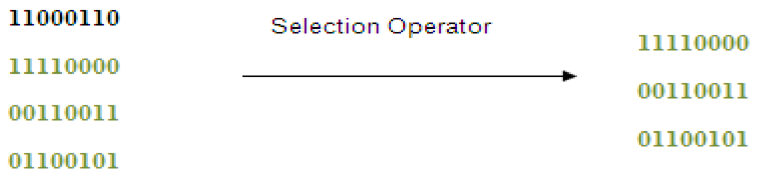
2. Fitness function

It determines how fit an individual is by giving him a **fitness score**. This score gives the probability to select an individual for reproduction.

3. Selection

It selects the fittest individuals and let them pass their genes to the next generation. The process, based on their fitness scores, selects two pairs of individuals (parents). After that, the process selects the ones with high fitness since they have more chance for reproduction.

Example



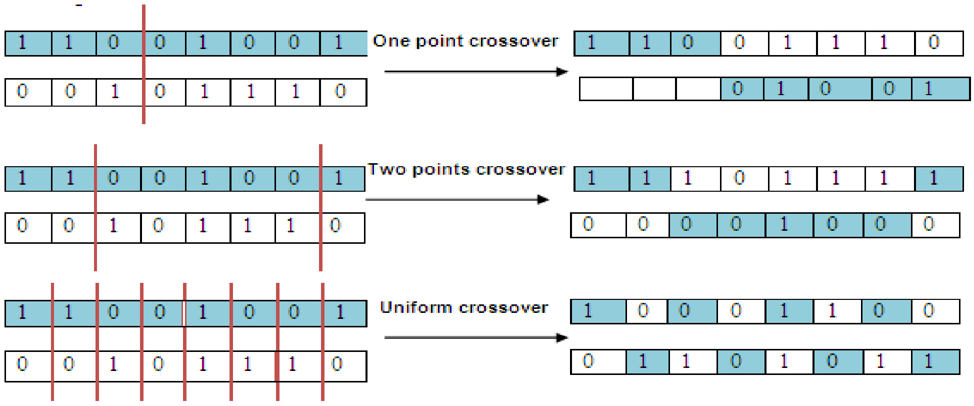
4. Crossover

It is the result when two chromosomes share their peculiarities and it allows the genetic mixing of the population and the application of the principle of inheritance of Darwin's theory.

For each pair of parents to be mated by the process, a **crossover point** is chosen randomly from within the genes. **Offspring** are created by exchanging the genes of parents among themselves until the crossover point is reached.

We add the new ones to the population.

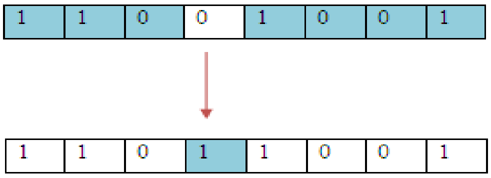
Example



5. Mutation

In certain new offspring formed, some of their genes can be subjected to a mutation with a low random probability. This implies that some of the bits in the bit string can be flipped. It occurs to maintain diversity within the population and **prevent premature convergence**.

Example



At the end, the algorithm terminates if the population has converged which means of it does not produce offspring that are different from the precedent generation. By that, it could be said that the genetic algorithm has provided a set of solutions to our problem.

2. Structure coding

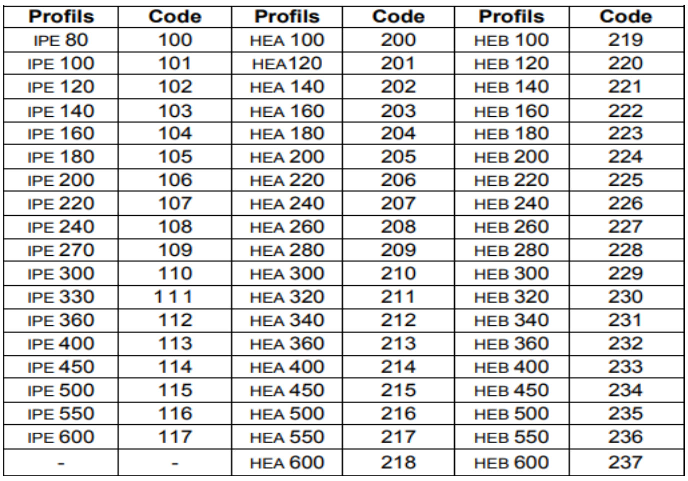
In **AG**, each possible design solution is coded by a chromosome that consists of three parts related to the three types of optimization variables.

For these three parts, each one is composed of a number of genes, which is equal to the number of design variables in a structure.

To facilitate the use of AG, the dimensional characteristics of different standard profiles (IPE, HEA, HEB...) are stored in a database or coded.

We suggest an integer coding that allows the distinction of the type of these profiles already mentioned and its number that represents its height. We also code the type of connections and supports of a design solution through a chain of integers.

1. Coding of standard profiles



Profils	Code	Profils	Code	Profils	Code
IPE 80	100	HEA 100	200	HEB 100	219
IPE 100	101	HEA120	201	HEB 120	220
IPE 120	102	HEA 140	202	HEB 140	221
IPE 140	103	HEA 160	203	HEB 160	222
IPE 160	104	HEA 180	204	HEB 180	223
IPE 180	105	HEA 200	205	HEB 200	224
IPE 200	106	HEA 220	206	HEB 220	225
IPE 220	107	HEA 240	207	HEB 240	226
IPE 240	108	HEA 260	208	HEB 260	227
IPE 270	109	HEA 280	209	HEB 280	228
IPE 300	110	HEA 300	210	HEB 300	229
IPE 330	111	HEA 320	211	HEB 320	230
IPE 360	112	HEA 340	212	HEB 340	231
IPE 400	113	HEA 360	213	HEB 360	232
IPE 450	114	HEA 400	214	HEB 400	233
IPE 500	115	HEA 450	215	HEB 450	234
IPE 550	116	HEA 500	216	HEB 500	235
IPE 600	117	HEA 550	217	HEB 550	236
-	-	HEA 600	218	HEB 600	237

2. Coding of assembly types/connections

Type of assembly used	Connection	**Code**
Core angles	Articulated	**0**
Overhanging end plate	Recessed	**1**
End plate without overhang	Semi-rigid	**2**
Core and sole angles	Semi-rigid	**3**
Extended end plate with stiffeners	**Semi-rigid**	**4**

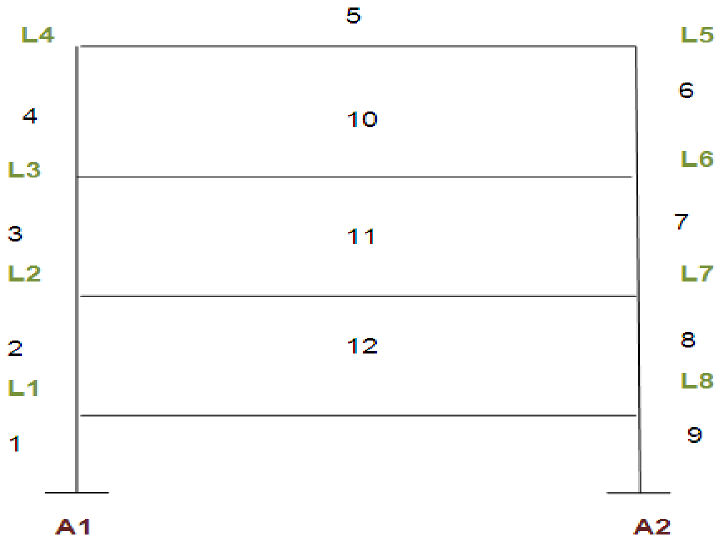
3. Coding of supports

Support	**Code**
Articulated post foot: End plate only	**0**

Recessed post foot: Post fixed by a stiffened end plate.	**1**

IV. Illustration

We use a structure of a chromosome for the coding of a **4-stage gate**.



We could express the **chromosome** as follows:

Barres												Liaisons (L)								Appuis(A)	
1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	1	2
100	112	110	200	105	202	115	200	114	115	116	100	1	4	4	4	4	4	4	1	1	1

The presented optimization method is used to search for the optimal design of the four-story portal frame. The optimization variables are the bars, the connections and the supports of the structure

This analysis is carried out in the **PEP Micro program** and allows the determination of the stresses acting on the elements of the structure as well as the displacements of its nodes. The determination of the stiffness and resistance characteristics of the semi-rigid connections is carried out based on the simplified **"SPRINT" model**

We use different tests to define the parameters: Population size (200), total number of generations (300), crossover probability (0.6) and mutation probability (0.2).

The results of the optimization of the structure are presented in the following table.

Variables	Solution1	Solution2
Bars	-	-
Connections	-	-

Supports	Semi-rigid	Classical supports
Total cost (Dh)	69960	81480
Cost Assemblies / Total Cost	16%	23%
Foundation cost / Total cost	14%	12%
Weight Assemblies / Total weight	5%	7%
total weight(KN)	36	40

We compare the design solution with classical assemblies with the solution obtained by adopting a semi-rigid modeling of the assemblies. The production of the second solution is more expensive. The use of semi-rigid connections allows obtaining gains on the global realization cost of the structure. In fact, the use of traditional connections leads to a greater complexity of the connections, thus higher costs of realization, without bringing a significant optimization at the level of the size of the used profiles or on the efforts to be transmitted to the foundations.

V. Perspectives of enlargement of the field of study

Nowadays, the research in this study's field continues despite the fact that this technique has given remarkable results until now. However, at present, the most limiting aspect of Genetic algorithms' expansion is undoubtedly **Convergence criteria** but there are some possibilities of exploration to allow their implementation.

Indeed, it is not easy in this optimization technique to learn about accurate data information. However, as generations go by, we can certainly use what is happening in the populations to learn fitness information. This would allow us to do more accurate modeling that would fit each problem.

Among the perspectives, **building sub-populations** that would evolve independently before joining each other. This would increase the probability of reaching the global optimum.

Moreover, there are some plans to expand the application of this new method to structures **regardless of materials' nature** used (**concrete or metal**) and to develop it using better graphical interfaces in order to facilitate the task of the users namely the engineers of the design office.

To conclude, there are two main ideas of developing this field of study. The first one concerns the parameters' properties and their relationship to the optimization algorithms and the second focuses on the development of new techniques for automatic adjustment of these parameters.

VI. Opinion about optimization's projects

Obviously, optimization projects of any kind will be more effective if a design office or even a large company carries them out.

In fact, the engineers working in these places try as much as possible to minimize the tasks and make their activity more efficient as well as delivering it within the deadline. Therefore, it is a question of reducing realization's time or minimizing the costs constituting an important part in the life of the projects through the reduction of the costs of the different elements being part of this project. Therefore, the optimization techniques allow achieving such ambitions. Moreover, this optimization, especially the one for the cost, will allow these engineers to devote the remaining amount to other activities that will enhance the project or make it environmentally friendly, especially since there are certainly ecological materials that are expensive. As an example of optimization techniques that are profitable for a design office or other, the study of this topic has reported the genetic algorithms since they minimize the overall cost of the project through the reduction of costs of metal structures that are used in these projects.

In conclusion, the optimization techniques have certainly a great benefit for the companies that are part of the civil engineering.

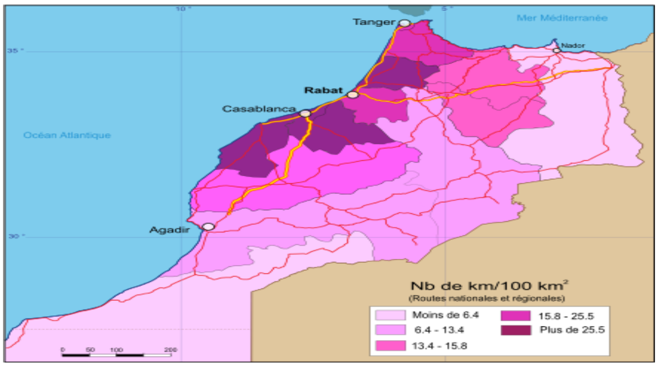
VII. Application in Morocco

The optimization technique of GA is certainly a profitable one for those who know how to take advantage of it. Moreover, as it is mentioned in this research, this technique, whose use is made at the level of the various engineering offices and the construction companies, is already benefited by Algeria even of other countries of Europe like Belgium. Moreover, in Algeria, at the laboratory of **materials and structural design associated with the University of Oran**, they were able to integrate it easily to achieve the desired goal of reducing the overall costs of several projects.

Frankly speaking, it is not foreseen if it is used in such construction or not since, it enters in the stage before project in the selection of the nature of the elements that the structure has (the supports, the connections and the bars). Moreover, the fact of implementing this technique in pre-project constitutes a confidential act and the job's secret of the office of study that is responsible.

If Morocco opts for such optimization, it will undoubtedly give birth to huge profits that will be spent in other problems that the project needs more expenses. If, for example, Morocco could figure out how to reintegrate this method into its subsequent projects, it would probably gain more than it would lose.

Example1: Widen the Casablanca-Rabat motorway axis: the central link in the Kingdom of Morocco's motorway network. It connects the economic capital and the administrative capital of the country over a length of about 100 km and concentrates on its route the majority of flows between the North, South and Center of the Kingdom



Example2: The project ensures **the connection of the new port of Nador West Med under construction with the highway network** for an envelope of 4.5 billion DH or the investment by **ONCF** for the acquisition of rolling stock for an amount of over 1.6 billion DH.
Therefore, it is already huge in terms of budgets as we can see. So, if the project has already implemented the method it will surely benefit from it, otherwise we do not really know because most of the design and control offices prefer to keep their working methodology confidential.

VIII. Conclusion

To conclude, in this research, we involved the use of Genetic Algorithms as an optimization technique in order to minimize the cost of steel structures and by that reducing the cost of a construction's project life.

To achieve this crucial study, the first thing done is formulating the problem that has as an objective the minimization of the global cost of a structure while respecting the various design constraints represented by the technological and regulatory constraints of resistance and the service of the structure.

After describing profoundly the subject matter, we continue the study by introducing the solution, which is the use of the algorithms alias GA and their implementation on a simple steel structure to grasp more the process. Before ending the topic, we gave ideas about the perspectives of enlargement of the study's field as well as the probability of implementing this technique in Morocco.

At the end, in deed, Genetic Algorithms could easily grasp problems considered difficult or requiring a significant amount of computing time with a classical algorithmic approach since they search in the space of admissible design solutions the optimal characteristics of the structure's elements that guarantee an optimal cost of the structure and respect the constraints.

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